Intercomparison of Soil Moisture Memory in Two Land Surface Models

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ABSTRACT

A heavy rain or a dry period can produce an anomaly in soil moisture, and the dissipation of this anomaly may take weeks to months. It is important to understand how land surface models (LSMs) used with atmospheric general circulation models simulate this soil moisture ‘‘memory,’’ because this memory may have profound implications for long-term weather prediction through land–atmosphere feedback.

In order to understand better the effect of precipitation and net radiation on soil moisture memory, the NASA Seasonal-to-Interannual Prediction Project (NSIPP) Catchment LSM and the Mosaic LSM were both forced with a wide variety of idealized climates. The imposed climates had average monthly precipitation ranging from 15 to 500 mm and monthly net radiations (in terms of water equivalent) ranging from 20 to 400 mm, with consequent changes in near-surface temperature and humidity. For an equivalent water holding capacity, the two models maximize memory in distinctly different climate regimes. Memory in the NSIPP Catchment LSM exceeds that in the Mosaic LSM when precipitation and net radiation are of the same order; otherwise, memory in the Mosaic LSM is larger.

The NSIPP Catchment and the Mosaic LSMs were also driven offline, globally, for a period of 15 yr (1979–93) with realistic atmospheric forcing. Global distributions of 1-month-lagged autocorrelation of soil moisture for boreal summer were computed. An additional global run with the NSIPP Catchment LSM employing the Mosaic LSM's water holding capacities was also performed. These three global runs show that while some of the intermodel difference in memory can be explained (following traditional interpretations) in terms of differences in water holding capacity and potential evaporation, much of the intermodal difference stems from differences in the parameterizations of evaporation and runoff.

1. Introduction

A period of heavy rainfall or drought can produce an anomaly in soil moisture that may take weeks or months to dissipate. In effect, the soil can ‘‘remember’’ the wet or dry weather conditions that caused the anomaly long after these conditions are forgotten by the atmosphere. Soil moisture memory can be characterized in various ways, including anomaly decay timescales and 1-month-lagged moisture autocorrelations.

Long-term records of soil moisture are not available in many parts of the world, and thus our ability to quantify soil moisture memory from soil moisture observations is strongly limited. The Global Soil Moisture Data Bank (Robock et al. 2000), however, does have substantial data, mainly in Asia. Soil moisture anomaly decay timescales of 2–3 months have been derived by analyzing in situ soil moisture data from stations in Russia (Vinnikov and Yeserkepova 1991; Vinnikov et al. 1996). Entin et al. (2000) derived timescales of about 2 months from Chinese, Mongolian, and Illinois data. Available data show that the timescales of soil moisture anomaly dissipation vary spatially (Vinnikov and Yeserkepova 1991), presumably due to spatial variability of surface characteristics and prevailing climatic conditions.

Soil moisture memory is particularly relevant to the seasonal prediction of precipitation, temperature, and other meteorological variables. This is because the persistence of a soil moisture anomaly into a forecast period allows the anomaly to influence meteorological variables during the forecast period—various modeling studies (e.g., Shukla and Mintz 1982; Oglesby and Erickson 1989; Koster and Suarez 1995, 1996b; Liu and Avissar 1999a,b; Dirmeyer 2000) have shown that the atmosphere responds somewhat predictably to anomalies in land surface moisture state. Indeed, initializing the land surface in a seasonal forecasting system may

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be as useful as initializing the system's coupled ocean model, particularly for summer forecasts in transition zones between dry and humid regions (Koster et al. 2000b).

The land surface model (LSM) of a seasonal forecasting system performs the water and energy budget calculations over the land surface and is thereby responsible for determining (and taking advantage of) soil moisture memory. Simulated memory can, in fact, be strongly LSM-dependent, and this can lead to forecast error. Depending on its structure, an LSM may underestimate memory relative to nature, thereby underestimating predictability in the system, or it may overestimate memory, leading to overconfident seasonal predictions. When relying on land moisture initialization in a seasonal prediction system, the nature of the LSM's simulated soil moisture memory must be well understood.

Delworth and Manabe (1988) pioneered the study of soil moisture memory in AGCMs, using a first-order Markov process model to relate memory to potential evaporation and soil water holding capacity. Koster and Suarez (2001) provide a more comprehensive equation that relates soil moisture autocorrelation to four separate features of the physical system: 1) seasonality in the statistics of the atmospheric forcing, 2) the sensitivity of evaporation to soil moisture in the LSM, 3) the sensitivity of runoff to soil moisture in the LSM, and 4) correlation of forcing with antecedent soil moisture. (See section 2.) They successfully tested the equation on the global scale against atmospheric general circulation model (AGCM) data. The equation provides a quantitative framework for analyzing a given LSM's memory characteristics and for pointing out how deficiencies in the LSM–atmosphere system may compromise the simulation of memory.

A potential, yet untested, value of the equation lies in its use to contrast the memory characteristics of different LSMs. Why, under the same atmospheric forcing, does one LSM preserve a soil moisture anomaly longer than another? Can we evaluate which LSM has the more realistic memory based on the factors that control it? In the present paper, through a series of ''offline'' experiments, we use the equation to contrast the memory behavior of the Mosaic LSM (Koster and Suarez 1996a) and the fundamentally different National Aeronautics and Space Administration (NASA) Seasonal-to-Interannual Prediction Project (NSIPP) Catchment LSM (Koster et al. 2000a). In the first experiment (section 3), a wide range of idealized precipitation and radiation forcing is applied to each LSM. The two LSMs are found to respond quite differently to the forcing; certain climatic regimes favor memory in the Mosaic LSM, whereas other regimes favor memory in the NSIPP Catchment LSM. The autocorrelation equation allows us to explain this climate dependence. In the second experiment (section 4), global arrays of realistic atmospheric forcing are applied to each model. This results not only in global arrays of soil moisture memory for each model, which can be directly compared, but also in global arrays of the factors that control each model's memory. Given the dearth of soil moisture observations on the global scale, it is the evaluation of these factors that may someday lead to an evaluation of the accuracy of simulated soil moisture memory.

5. Discussion and summary

In this paper, we address the problem of characterizing intermodel differences in simulated soil moisture memory. We use as a framework for this analysis the autocorrelation equation, (4), derived by Koster and Suarez (2001). The equation helps explain differences in memory in terms of differences in the structures of the LSMs. The relevance of the equation to this analysis is confirmed by the agreement in Fig. 3 between the autocorrelations estimated by the equation and those actually simulated by the two LSMs studied.

The idealized experiment in section 4a contrasted the LSM behaviors in a multitude of different climates, isolating in particular the way in which their evaporation and runoff production mechanisms affect simulated memory. While the experiment was limited by the neglect of land cover, soil, and water holding capacity differences between the LSMs (a deficiency that could, in principle, be overcome by repeating the experiment many times, under many different sets of surface properties), it does indicate that the NSIPP catchment LSM tends to have higher soil moisture memory when precipitation and net radiation (scaled into units of water equivalent) are approximately in balance. A similar conclusion is reached through analysis of the less idealized, global memory calculations in section 4b(1) (see Fig. 2). The reasons for the difference in model behavior involve intermodel differences in the sensitivities of runoff and evaporation to soil moisture, as embodied in the parameters a and c of (4). When precipitation and net radiation are roughly equal, the sensitivities are, for various reasons, smaller in the NSIPP Catchment LSM (Figs. 1d,e), and thus memory in this model is higher. When precipitation overwhelms net radiation, the NSIPP Catchment LSM's baseflow rate becomes more responsive to changes in soil moisture than the Mosaic LSM's drainage rate, leading to a higher a value and thus to lower memory relative to the Mosaic LSM. When net radiation overwhelms precipitation, the ''dynamic wilting area'' in the NSIPP Catchment LSM—absent in the Mosaic LSM—gives it a higher evaporation sensitivity to soil moisture (a higher c value) and thus a lower soil moisture memory.

As an aside, we note that for seasonal prediction, the sensitivity of evaporation to soil moisture should be neither too high nor too low. When the sensitivity is too high, soil moisture memory is reduced, as discussed earlier. When it is too low, however, the atmosphere cannot respond to a soil moisture anomaly, even if it persists well into the forecast period (Koster and Suarez 2003). These two opposing effects suggest the existence of an optimal, intermediate value for the sensitivity. This is being explored in ongoing research.